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Saruwatari

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(54) **ZOOM LENS AND IMAGE PICKUP APPARATUS HAVING THE ZOOM LENS**

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G02B 15/14 (2006.01)

(52) **U.S. Cl.** **359/686**; 359/683

(58) **Field of Classification Search** 359/676, 359/683, 686

See application file for complete search history.

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(74) *Attorney, Agent, or Firm*—Canon USA Inc IP Div

(57) **ABSTRACT**

A zoom lens includes, in order from an object side to an image side, a first lens unit having a positive refractive power and configured to move along an optical axis during zooming, a second lens unit having a negative refractive power and configured to move with a locus convex towards the image side during zooming, a third lens unit having a positive refractive power, and a fourth lens unit having a negative refractive power. The first lens unit is located closer to the object side at a telephoto end than at a wide-angle end and the second lens unit is located closer to the image side at the telephoto end than at the wide-angle end. A focal length of the second lens unit (f2), a focal length of the zoom lens at the wide-angle end (fw), and a focal length of the zoom lens at the telephoto end (ft) are appropriately set.

11 Claims, 13 Drawing Sheets

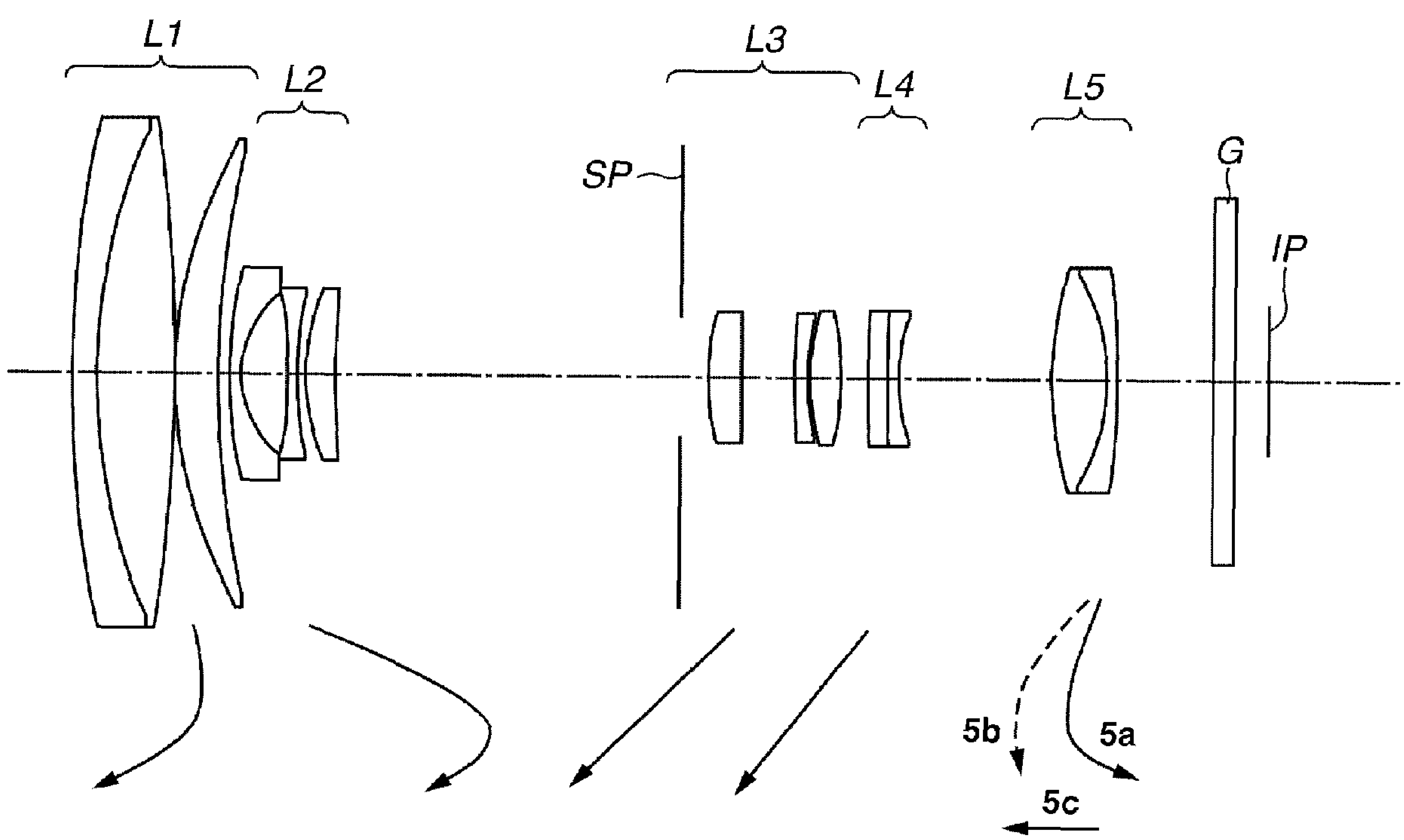


FIG.1

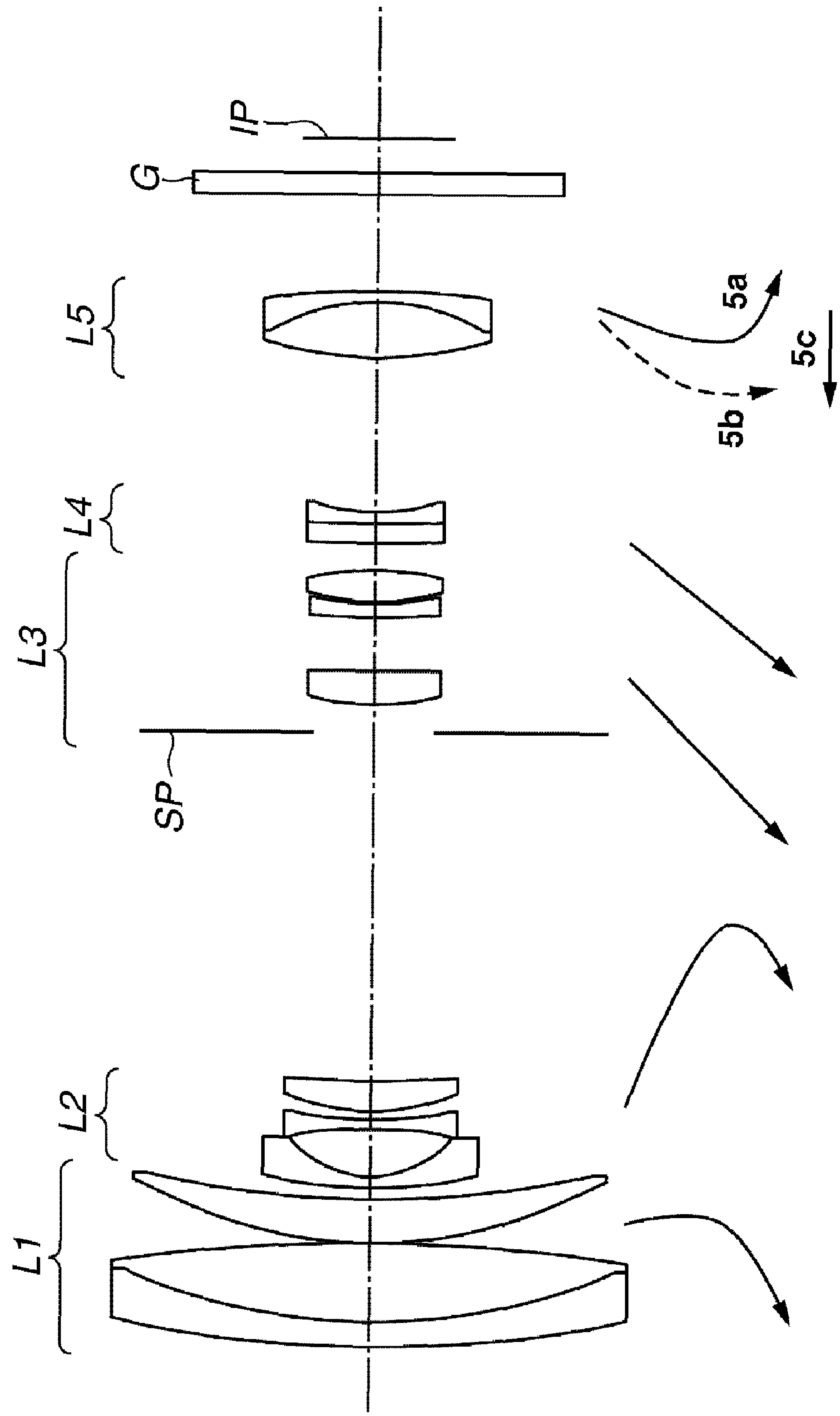
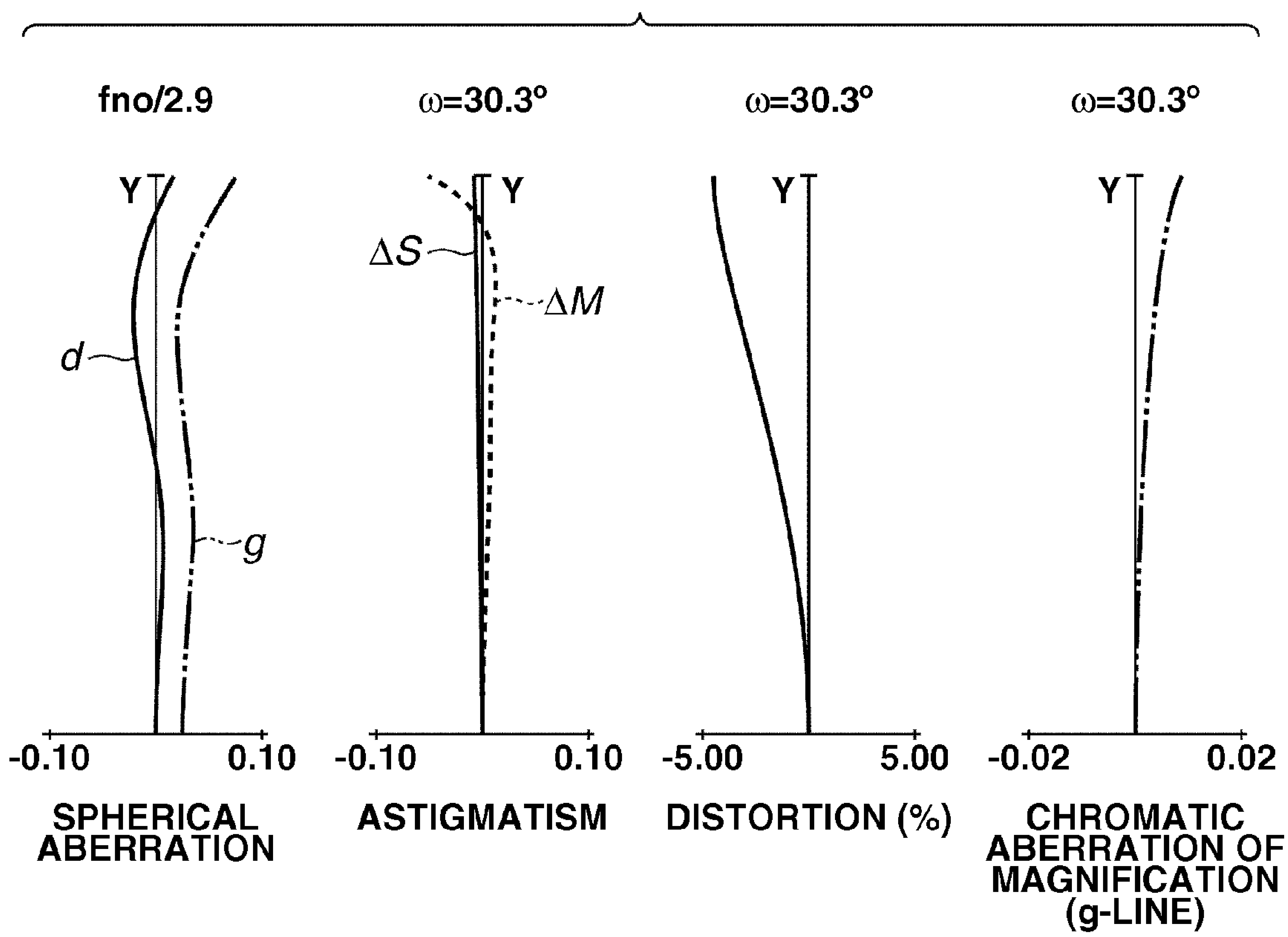


FIG.2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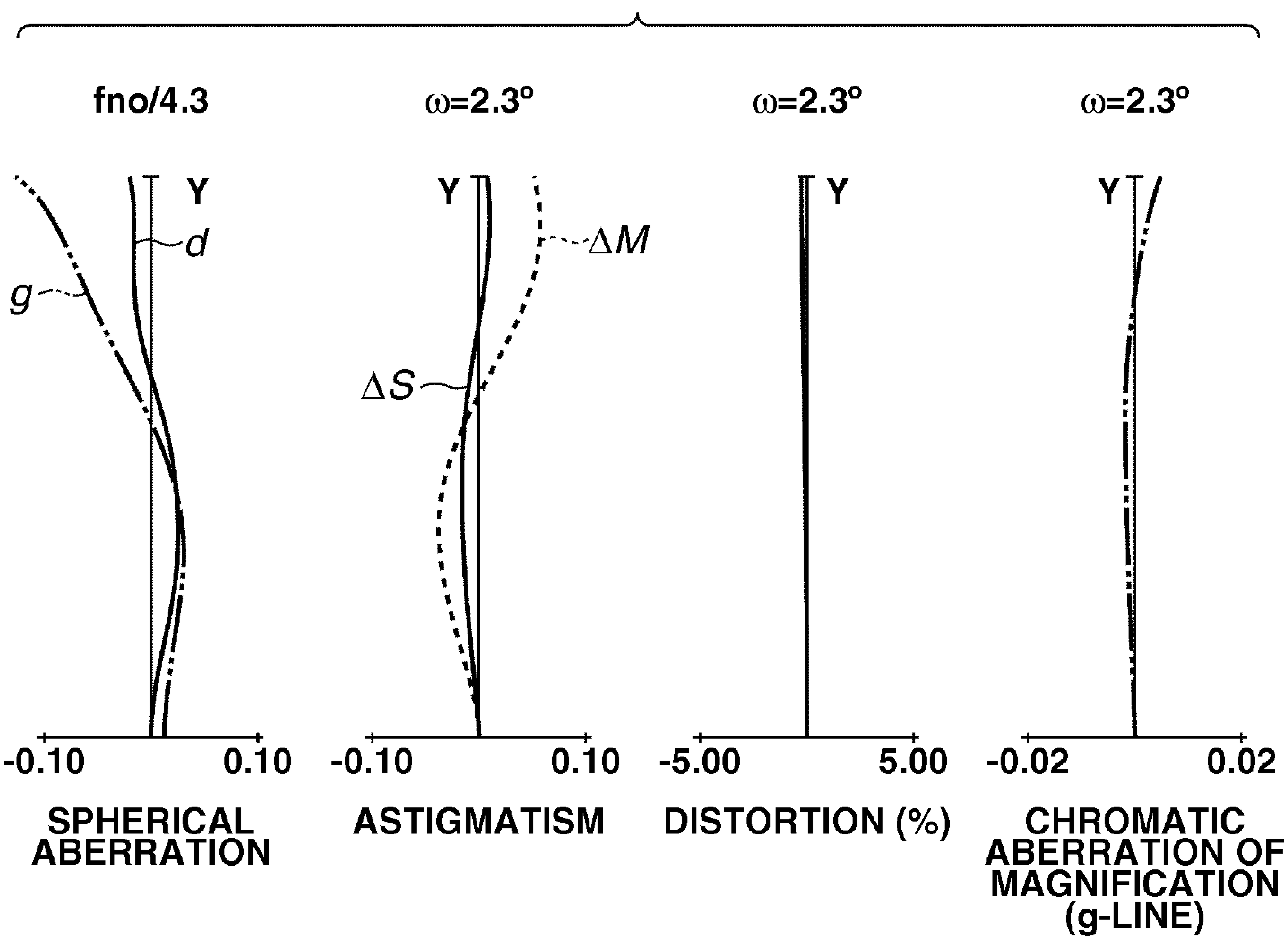
SPHERICAL ABERRATION
ASTIGMATISM
DISTORTION (%)
CHROMATIC ABERRATION OF MAGNIFICATION (g-LINE)

FIG.3



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SPHERICAL ABERRATION
ASTIGMATISM
DISTORTION (%)
CHROMATIC ABERRATION OF MAGNIFICATION (g-LINE)

FIG.4

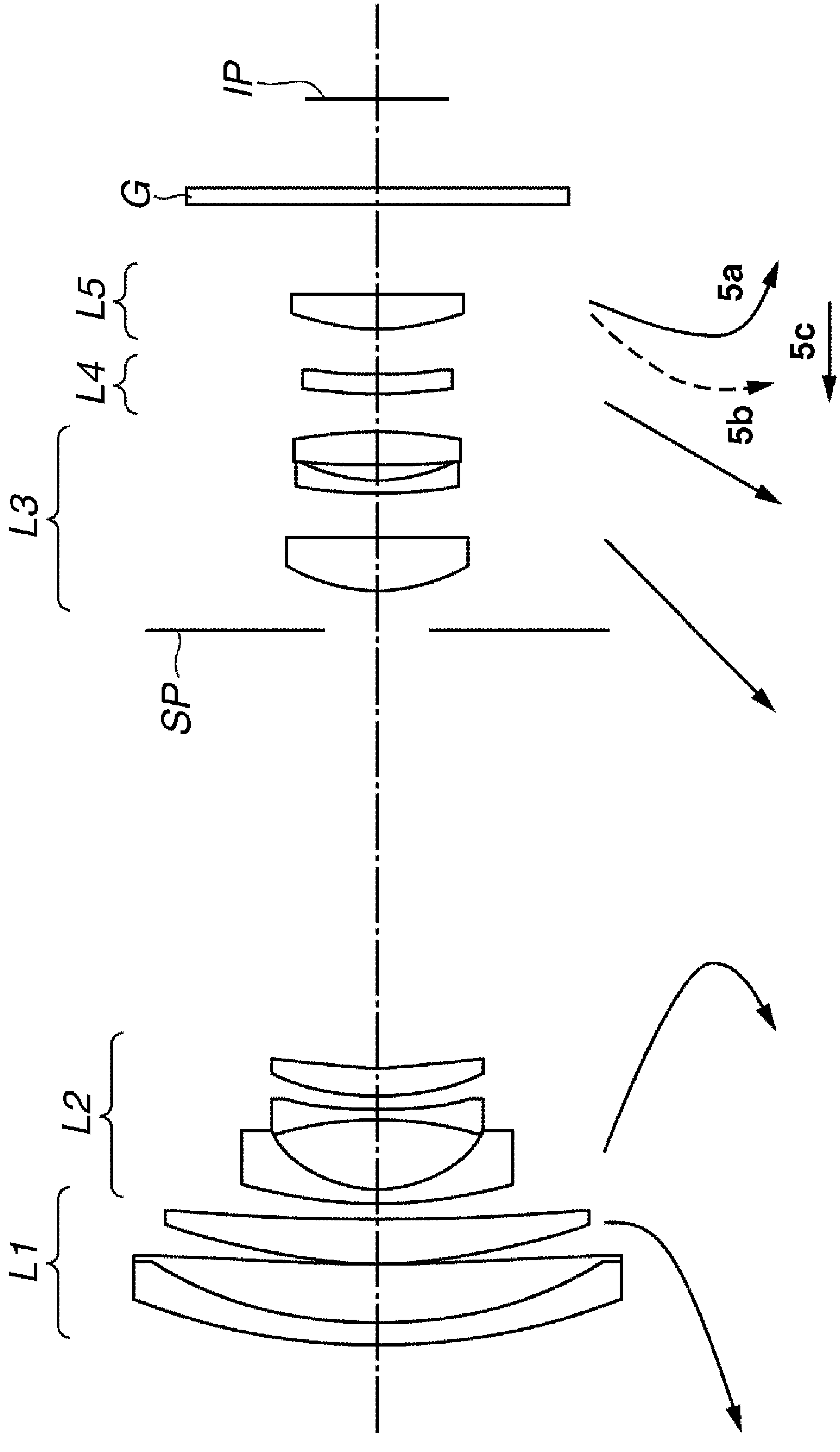
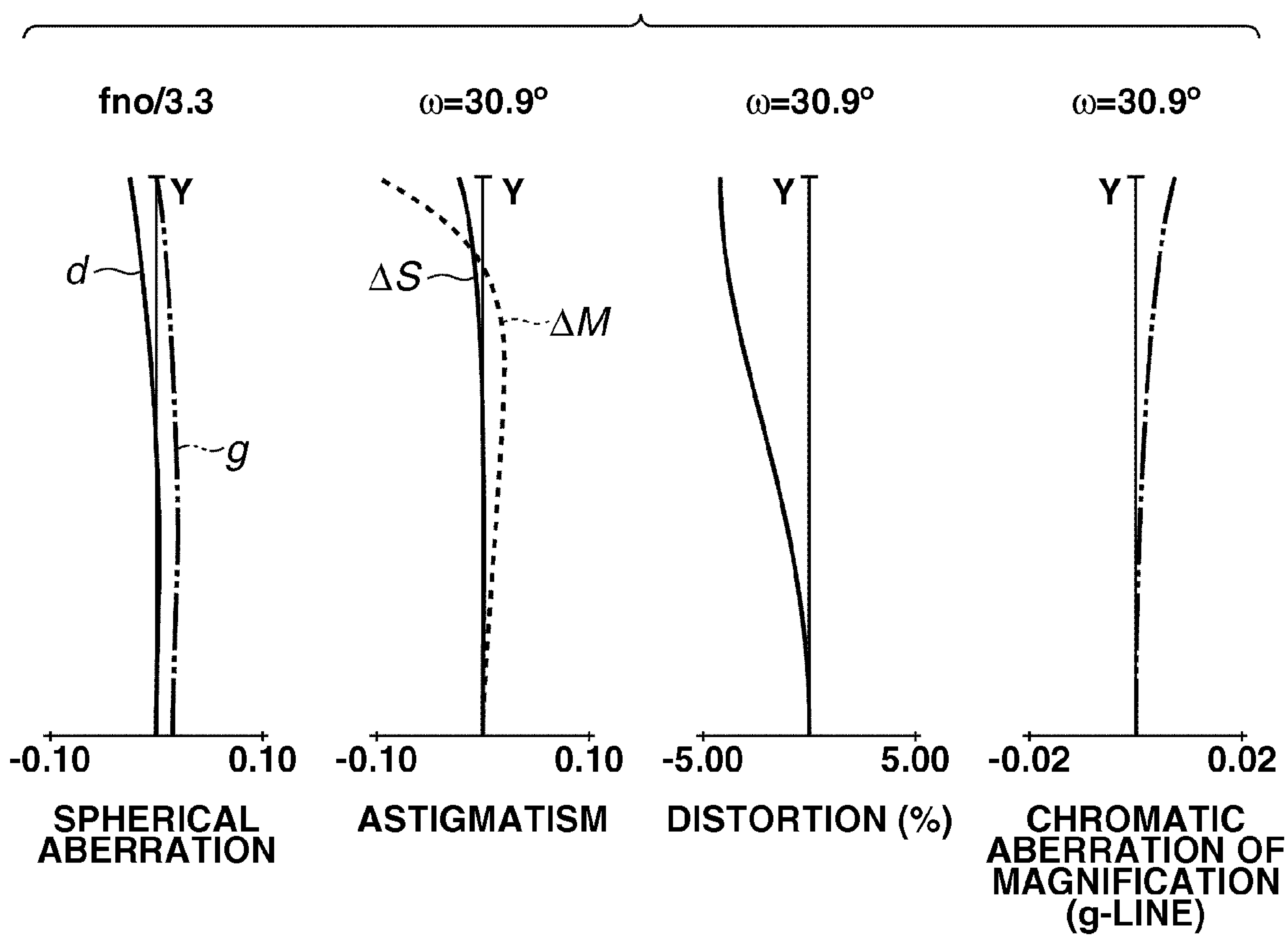


FIG.5



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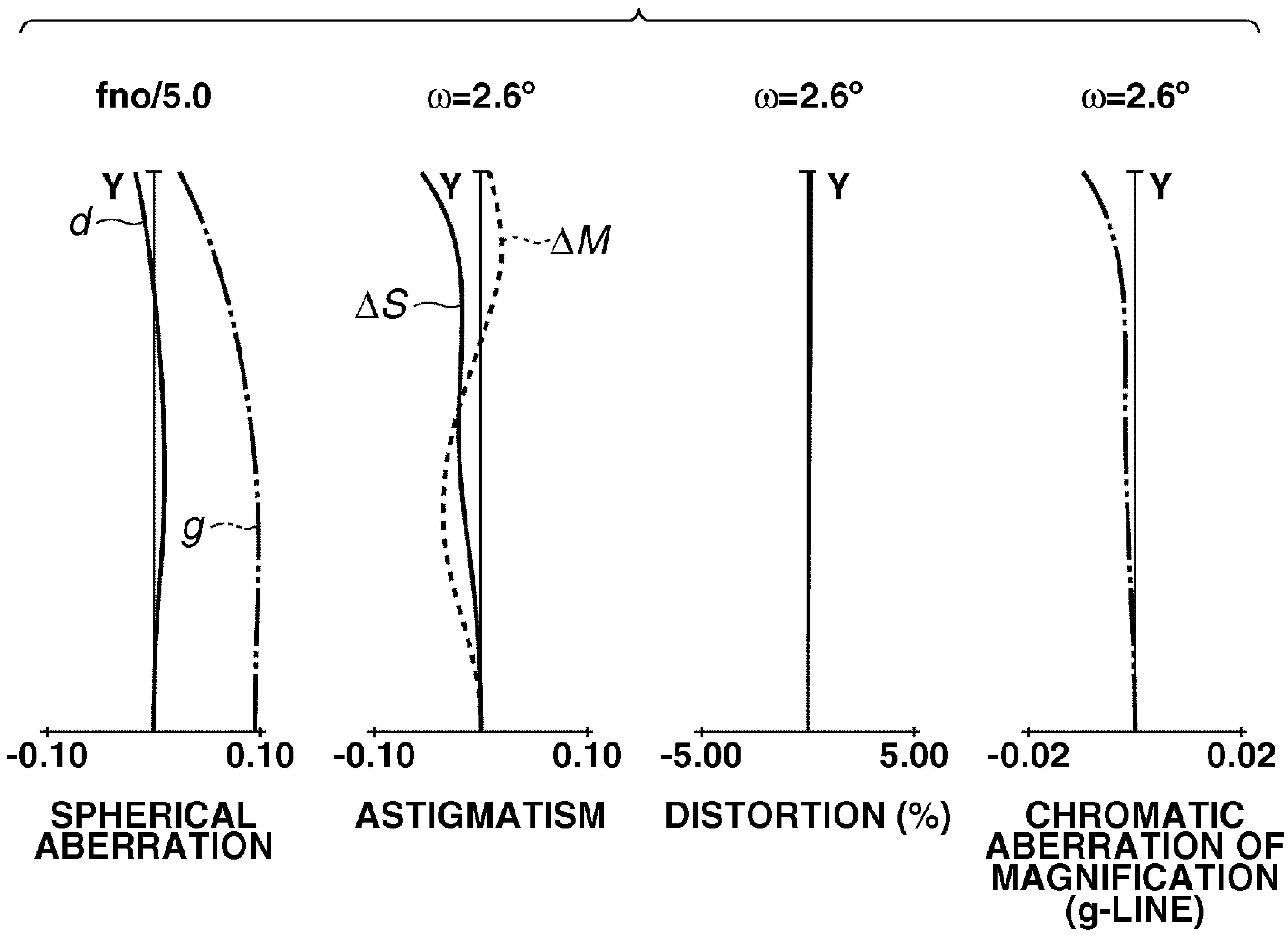
SPHERICAL ABERRATION
ASTIGMATISM
DISTORTION (%)
CHROMATIC ABERRATION OF MAGNIFICATION (g-LINE)

FIG.6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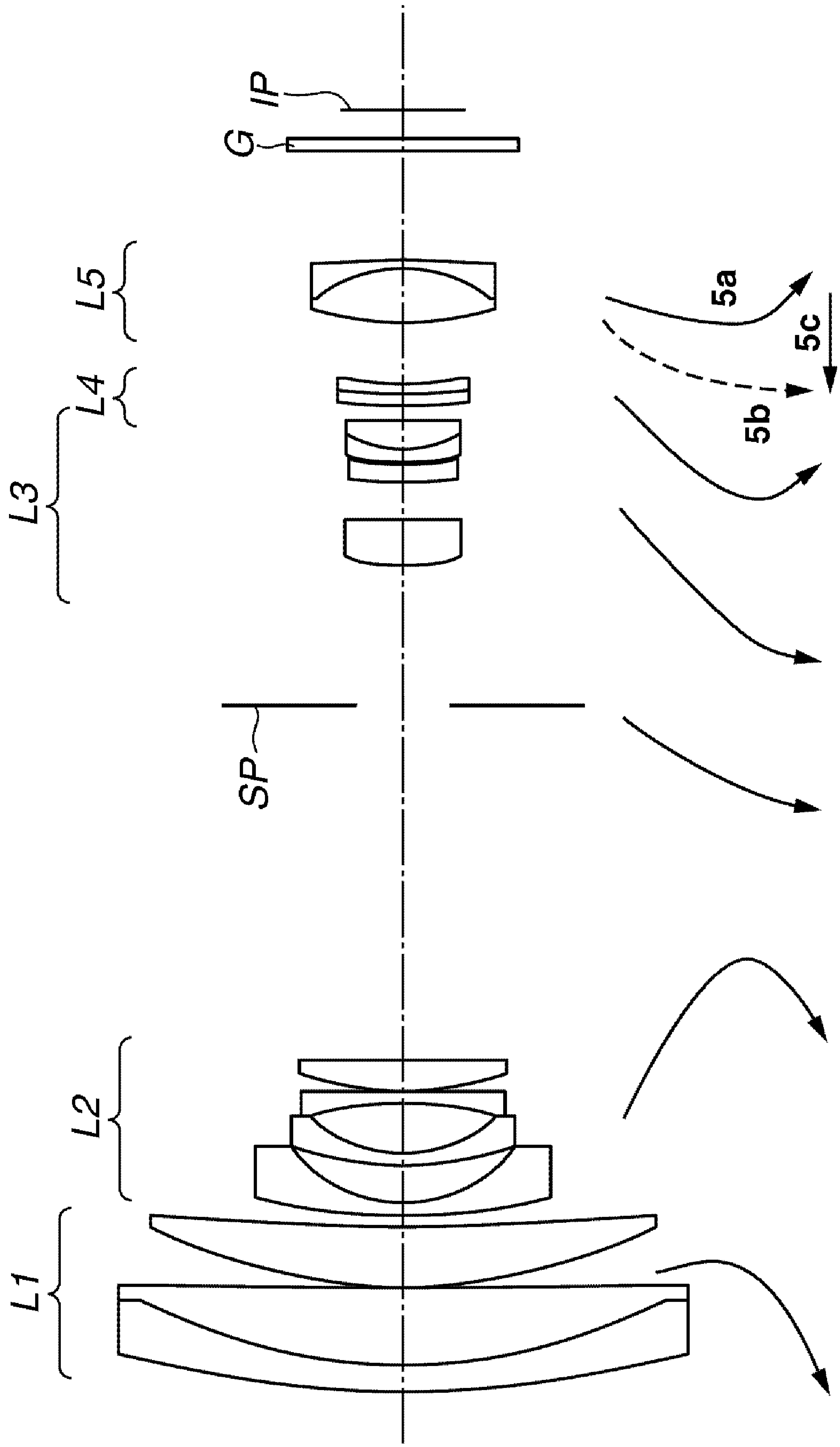
SPHERICAL ABERRATION
ASTIGMATISM
DISTORTION (%)
CHROMATIC ABERRATION OF MAGNIFICATION (g-LINE)

FIG.7



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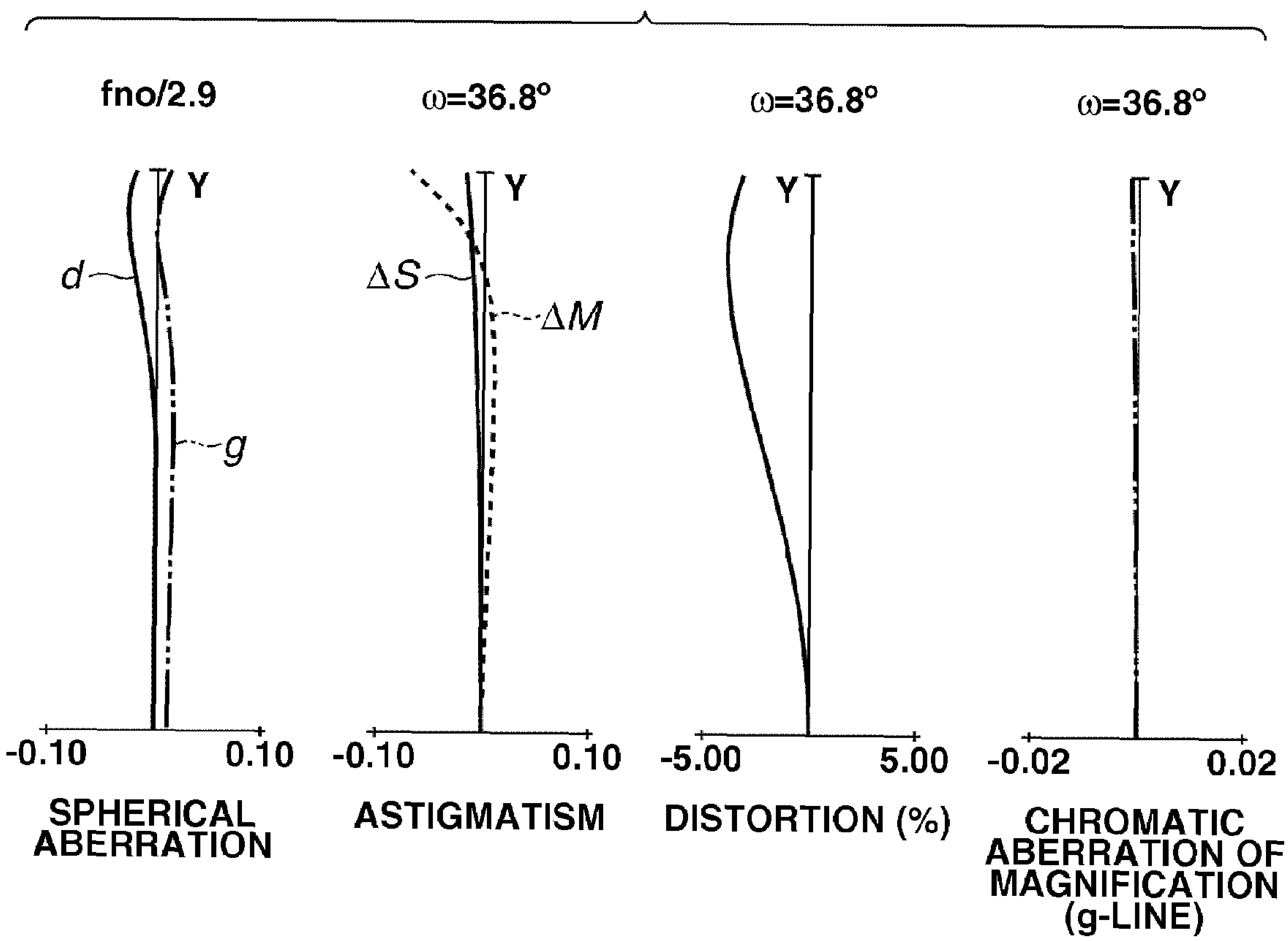
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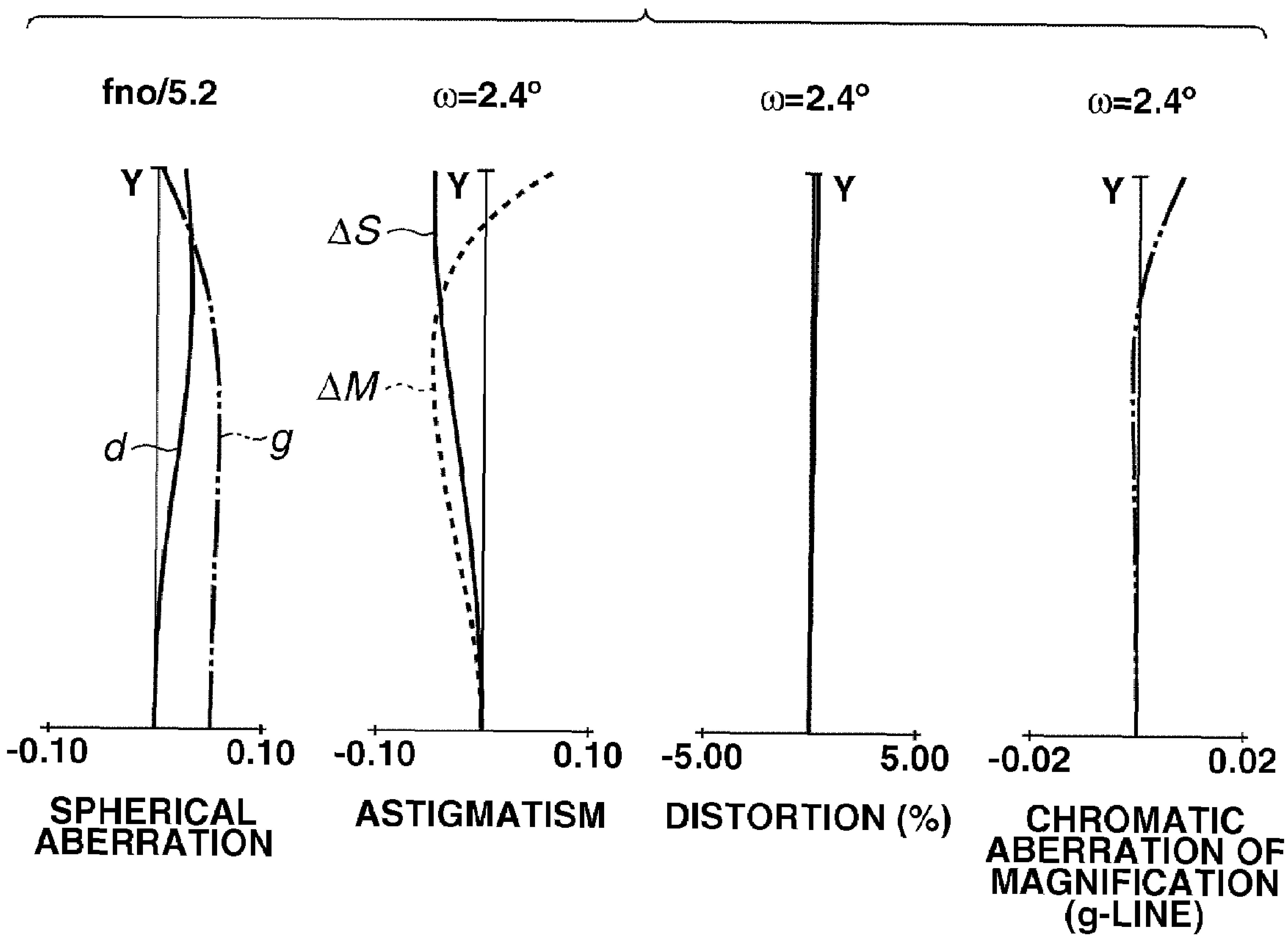
SPHERICAL ABERRATION
ASTIGMATISM
DISTORTION (%)
CHROMATIC ABERRATION OF MAGNIFICATION (g-LINE)

FIG.9



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ASTIGMATISM
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DISTORTION (%)
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CHROMATIC ABERRATION OF MAGNIFICATION (g-LINE)

FIG.10

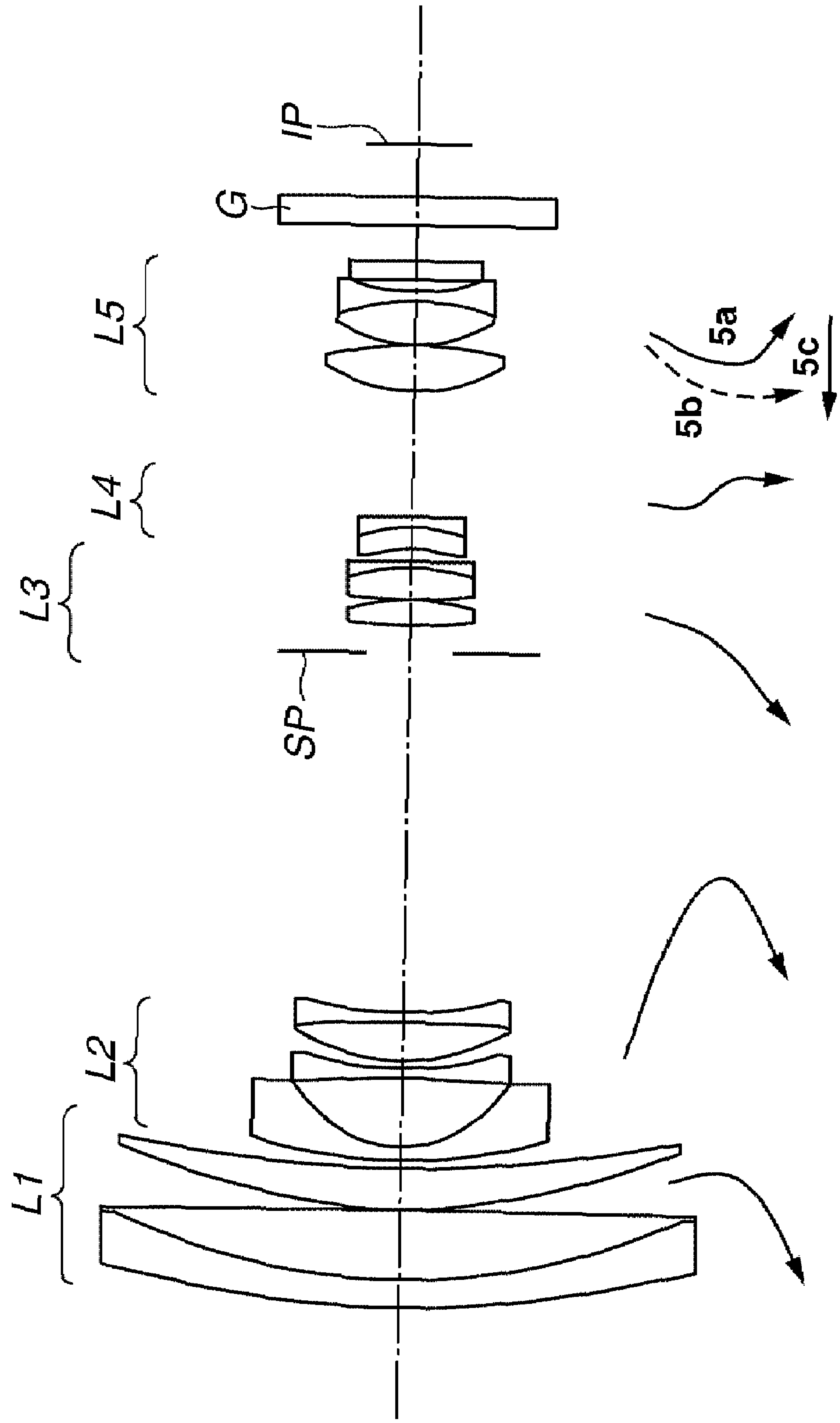
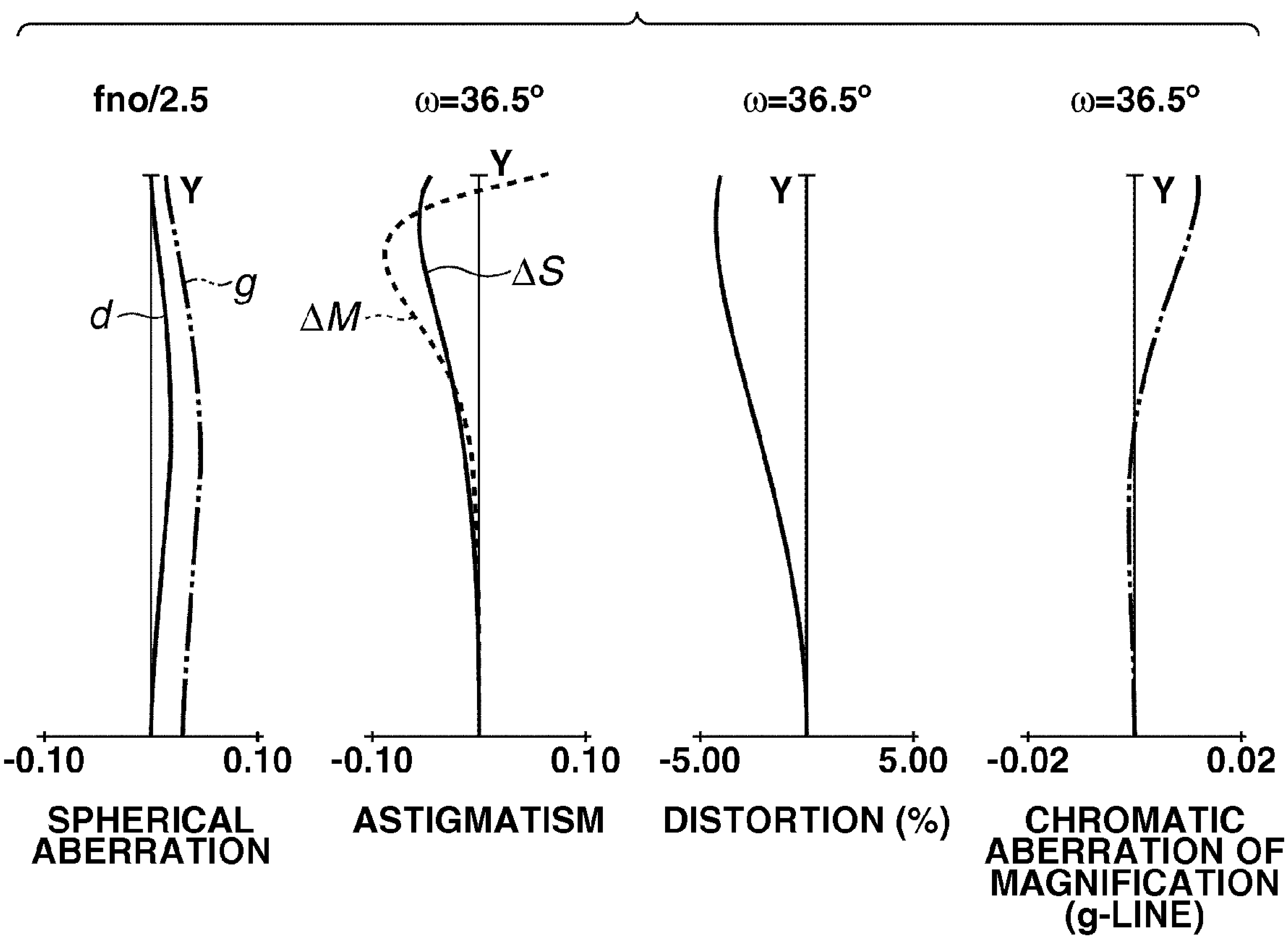


FIG.11



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DISTORTION (%)
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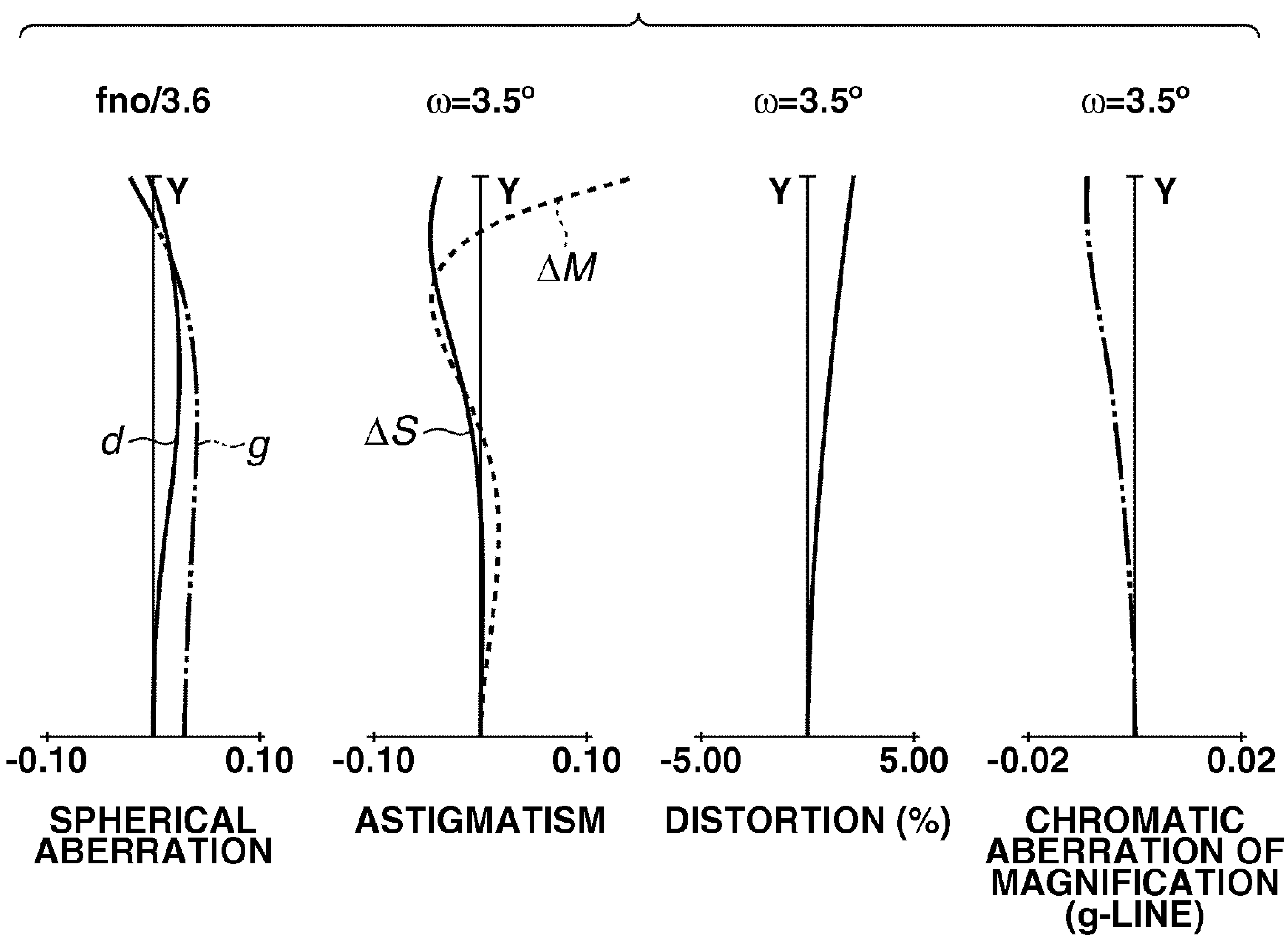
CHROMATIC ABERRATION OF MAGNIFICATION (g-LINE)

FIG.12



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DISTORTION (%)
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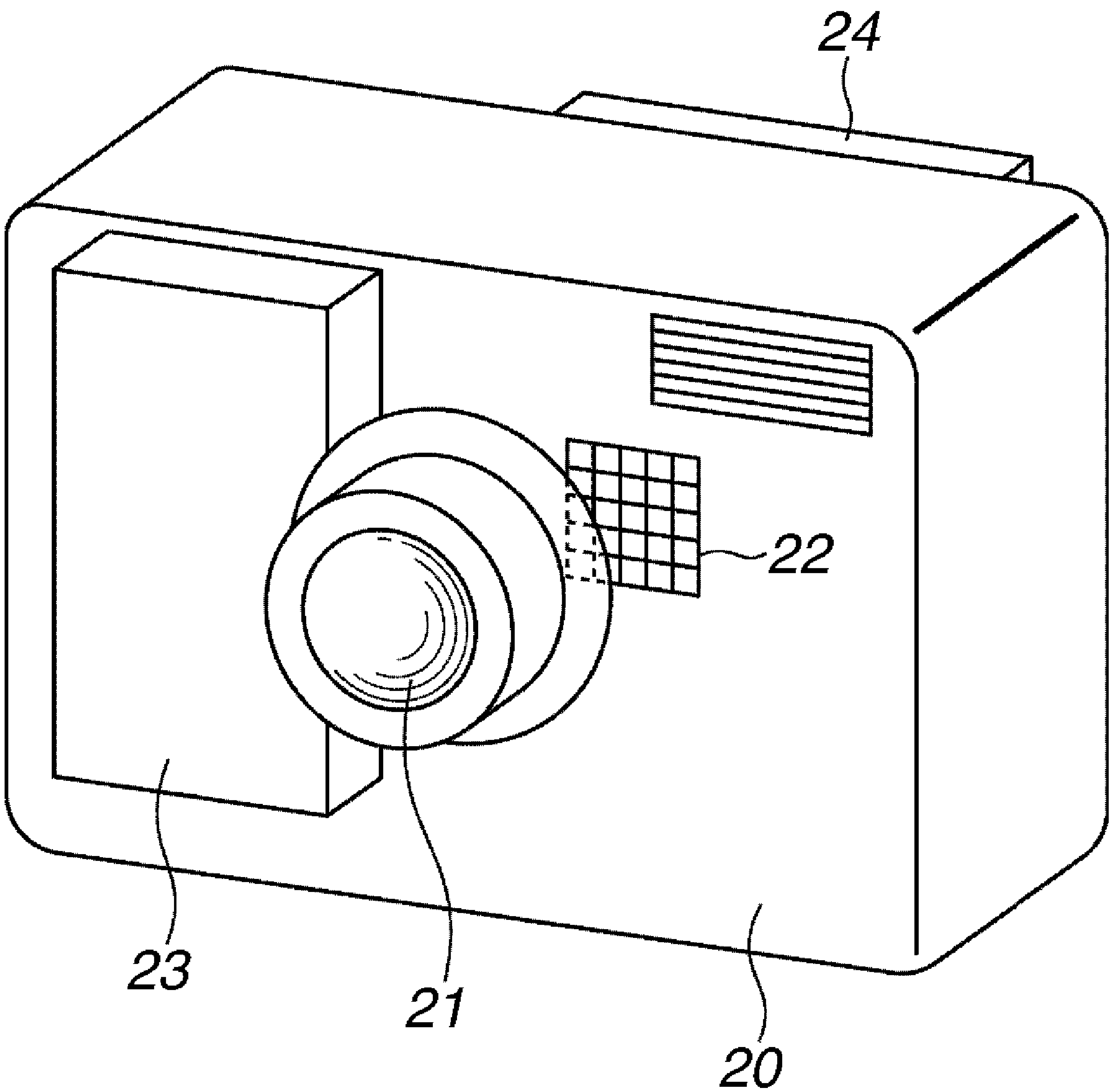
CHROMATIC ABERRATION OF MAGNIFICATION (g-LINE)

FIG.13



ZOOM LENS AND IMAGE PICKUP APPARATUS HAVING THE ZOOM LENS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a zoom lens and an image pickup apparatus having the zoom lens. More specifically, the present invention relates to a zoom lens and an image pickup apparatus, such as a video camera, a digital still camera, and a television camera, and a silver-halide film camera having the zoom lens.

2. Description of the Related Art

In recent years, an image pickup apparatus has a high functional performance and is small in size. Accordingly, it is desired by the market that a photographic optical system used in such an image pickup apparatus has a high resolution and a high zoom ratio and that the entire length of the lens unit is short.

A positive lead type zoom lens, whose lens unit located closest to the object side has a positive refractive power, can relatively easily achieve a high zoom ratio with a small entire lens unit size.

In this regard, U.S. Pat. No. 5,687,401 and Japanese Patent Application Laid-Open No. 11-352401 each discuss a positive lead type four-unit zoom lens. The zoom lens includes four lens units, namely, in order from the object side to the image side, a lens unit having a positive refractive power, a lens unit having a negative refractive power, a lens unit having a positive refractive power, and a lens unit having a negative refractive power, and performs zooming by moving a plurality of lens units.

Furthermore, U.S. Pat. Nos. 6,404,561, 7,177,092, 7,218,458, U.S. Patent Application Publication No. US 2003/0076591 A1, and Japanese Patent Application Laid-Open No. 2002-228931 each discuss a positive lead type five-unit zoom lens. The zoom lens includes five lens units, namely, in order from the object side to the image side, a lens unit having a positive refractive power, a lens unit having a negative refractive power, a lens unit having a positive refractive power, a lens unit having a negative refractive power, and a lens unit having a positive refractive power, and performs zooming by moving a plurality of lens units.

In the case of using a five-unit zoom lens, the vertical position (height) of an off-axis ray passing through the front lens can be lowered compared to that in the case of using a four-unit zoom lens. Accordingly, in this case, the front lens diameter can be reduced while achieving a high zoom ratio.

In addition, U.S. Pat. No. 7,336,419 discusses a positive lead type five-unit zoom lens, which is capable of correcting an image shake occurring when the zoom lens unit is vibrated by moving the third lens unit in the direction perpendicular to the optical axis.

Generally, in order to achieve a zoom lens having a predetermined zoom ratio and whose entire size is small, it is useful to increase a refractive power of each lens unit constituting the zoom lens with a reduced number of lens elements.

However, in this case, the lens thickness of the lens constituting the zoom lens may increase if the refractive power of each surface of the zoom lens is increased. Thus, the entire size of the lens cannot be appropriately reduced. Accordingly, in this case, it is difficult to correct various aberrations.

Furthermore, in this case, the amount of error, e.g., tilting of the lens or lens unit, occurring when retracting each lens unit at the time of nonuse of a camera may become large. If the sensitivity of the lens or lens unit is high, an optical performance may degrade or an image shake may occur during zooming.

Therefore, with respect to a zoom lens, it is useful that the lens or lens unit has as low a sensitivity as possible to achieve a high optical performance. In the case of a positive lead type zoom lens, in order to achieve a high optical performance and a high zoom ratio at the same time as well as to achieve a small-sized zoom lens, it is necessary to apply an appropriate setting for each component of the zoom lens.

More specifically, it is necessary to appropriately set a zoom type (the number of lens units and the refractive power of each lens unit), a moving locus of moving of each lens unit during zooming, and a magnification allocation for each lens unit.

If these settings are not appropriate, the entire zoom lens may become large-sized to achieve a high zoom ratio. Furthermore, in this case, variation of various aberrations occurring during zooming may increase. Therefore, it becomes very difficult to achieve a high optical performance over the entire zooming range and the entire image plane.

SUMMARY OF THE INVENTION

The present invention is directed to a zoom lens whose entire size is small, capable of achieving a high zoom ratio and having a high optical performance over the entire zooming range from the wide-angle end to the telephoto end, and is directed to an image pickup apparatus using the zoom lens.

According to an aspect of at least one exemplary embodiment of the present invention, a zoom lens includes, in order from an object side to an image side, a first lens unit having a positive refractive power and configured to move along an optical axis during zooming, a second lens unit having a negative refractive power and configured to move with a locus convex towards the image side during zooming, a third lens unit having a positive refractive power, and a fourth lens unit having a negative refractive power. The first lens unit is located closer to the object side at a telephoto end than at a wide-angle end, and the second lens unit is located closer to the image side at the telephoto end than at the wide-angle end. A focal length of the second lens unit (f**2**), a focal length of the zoom lens at the wide-angle end (fw), and a focal length of the zoom lens at the telephoto end (ft) satisfy the following condition:

$$-0.7<f2/\sqrt{(fw\cdot ft)}<-0.2.$$

Further features and aspects of the present invention will become apparent from the following detailed description of exemplary embodiments with reference to the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate exemplary embodiments, features, and aspects of the invention and, together with the description, serve to explain the principles of the present invention.

FIG. **1** is a lens cross section illustrating a zoom lens at the wide-angle end according to a first exemplary embodiment of the present invention.

FIG. **2** is an aberration chart for the zoom lens at the wide-angle end in numerical example 1 corresponding to the first exemplary embodiment of the present invention.

FIG. **3** is an aberration chart for the zoom lens at the telephoto end in numerical example 1 corresponding to the first exemplary embodiment of the present invention.

FIG. **4** is a lens cross section illustrating a zoom lens at the wide-angle end according to a second exemplary embodiment of the present invention.

FIG. **5** is an aberration chart for the zoom lens at the wide-angle end in numerical example 2 corresponding to the second exemplary embodiment of the present invention.

FIG. **6** is an aberration chart for the zoom lens at the telephoto end in numerical example 2 corresponding to the second exemplary embodiment of the present invention.

FIG. **7** is a lens cross section illustrating a zoom lens at the wide-angle end according to a third exemplary embodiment of the present invention.

FIG. **8** is an aberration chart for the zoom lens at the wide-angle end in numerical example 3 corresponding to the third exemplary embodiment of the present invention.

FIG. **9** is an aberration chart for the zoom lens at the telephoto end in numerical example 3 corresponding to the third exemplary embodiment of the present invention.

FIG. **10** is a lens cross section illustrating a zoom lens at the wide-angle end according to a fourth exemplary embodiment of the present invention.

FIG. **11** is an aberration chart for the zoom lens at the wide-angle end in numerical example 4 corresponding to the fourth exemplary embodiment of the present invention.

FIG. **12** is an aberration chart for the zoom lens at the telephoto end in numerical example 4 corresponding to the fourth exemplary embodiment of the present invention.

FIG. **13** illustrates components of an image pickup apparatus according to an exemplary embodiment of the present invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Various exemplary embodiments, features, and aspects of the present invention will be described in detail below with reference to the drawings. It is to be noted that the relative arrangement of the components, the numerical expressions, and numerical values set forth in these embodiments are not intended to limit the scope of the present invention.

A zoom lens according to an exemplary embodiment of the present invention includes, in order from the object side to the image side, at least four lens units, namely, a first lens unit having a positive refractive power configured to move along an optical axis during zooming, a second lens unit having a negative refractive power configured to move with a locus convex towards the image side during zooming, a third lens unit having a positive refractive power, and a fourth lens unit having a negative refractive power.

The zoom lens according to an exemplary embodiment of the present invention is a photographic lens system used in an image pickup apparatus, such as a video camera, a digital camera, or a silver-halide film camera.

In each lens cross section, the left portion of the drawing is an object side and the right portion thereof is an image side. The zoom lens according to an exemplary embodiment can be used as a projection lens of a projector. In this case, the left portion of each lens cross section is a screen side and the right portion of each lens cross section corresponds to a projection image side.

In each lens cross section, the zoom lens includes a first lens unit L**1** having a positive refractive power (optical power: reciprocal of the focal length), a second lens unit L**2** having a negative refractive power, a third lens unit L**3** having a positive refractive power, a fourth lens unit L**4** having a negative refractive power, and a fifth lens unit L**5** having a positive refractive power.

An aperture stop SP is located on the object side of the third lens unit L**3**. "G" denotes an optical block, such as an optical filter, a face plate, a crystal low-pass filter, or an infrared ray cut-off filter.

"IP" denotes an image plane. In the case of using the zoom lens as a photographic optical system for a video camera or a digital still camera, a photosensitive surface, which is equivalent to a film surface of a silver-halide film camera, is located on an imaging plane of a solid-state image sensor (photoelectric conversion element), such as a charge-coupled device (CCD) sensor or a complementary metal-oxide semiconductor (CMOS) sensor.

In each of the aberration charts, "d" denotes d-line light and "g" denotes g-line light. "ΔM" denotes a meridional image surface. "ΔS" denotes a sagittal image surface. Chromatic aberration of magnification is expressed with g-line light. "ω" denotes a half angle of view. "Fno" denotes F-number.

The Y-axis in the spherical aberration's graph is entrance pupil radius, and the Y-axis in the astigmatism's, distortion's, and chromatic aberration of magnification's graphs is image height.

Note that the "wide-angle end" and the "telephoto end" each refer to a zoom position at which a magnifying lens unit is located at an edge of a range in which it is mechanically movable along the optical axis.

In an exemplary embodiment, each lens unit is moved during zooming from the wide-angle end to the telephoto end as indicated with an arrow. More specifically, in the first and second exemplary embodiments, the first lens unit L**1** moves with a locus convex towards the image side during zooming from the wide-angle end to the telephoto end, as illustrated in FIG. **1** and FIG. **4**.

In addition, the second lens unit L**2** moves with a locus convex towards the image side.

Moreover, the third lens unit L**3** moves towards the object side. The fourth lens unit L**4** moves towards the object side. The fifth lens unit L**5** moves with a locus convex towards the object side. The aperture stop SP moves integrally with the third lens unit L**3** during zooming.

Furthermore, an exemplary embodiment of the present invention employs a rear focus type focusing method. The "rear focus type focusing method" refers to a method for performing focusing by moving the fifth lens unit L**5** along the optical axis. During focusing from an infinitely-distant object to a closest object at the telephoto end, the fifth lens unit L**5** is caused to move forward as indicated with an arrow **5***c*.

Curves **5***a* and **5***b* each indicate a moving locus along which the fifth lens unit L**5** is actually moved for correcting variation of the image plane, which may occur during zooming from the wide-angle end to the telephoto end at the time of focusing on an infinitely-distant object and a closest object, respectively.

In the third exemplary embodiment illustrated in FIG. **7**, the first lens unit L**1** moves with a locus convex towards the image side during zooming from the wide-angle end to the telephoto end as illustrated with an arrow in FIG. **7**.

In addition, the second lens unit L**2** moves with a locus convex towards the image side. Moreover, the third lens unit L**3** moves towards the object side. The fourth lens unit L**4** and the fifth lens unit L**5** move with a locus convex towards the object side.

The aperture stop SP moves towards the object side independently from the lens units. The fifth lens unit L**5** moves to perform focusing.

The moving locus with which the fifth lens unit L**5** moves for focusing is similar to that in the first and second exemplary embodiments.

The fourth exemplary embodiment illustrated in FIG. **10** is different from the first and second exemplary embodiments (FIGS. **1** and **4**) in the point that in the fourth exemplary embodiment, the fourth lens unit L**4** moves nonlinearly towards the image side during zooming from the wide-angle end to the telephoto end. Other points of the configuration of the fourth exemplary embodiment are similar to those in the first and second exemplary embodiments.

In an exemplary embodiment, the first lens unit L**1** and the third lens unit L**3** are located closer to the object side at the telephoto end than at the wide-angle end. Thus, the entire lens length can be reduced at the wide-angle end while achieving a high zoom ratio.

At this time, the second lens unit L**2** moves with a locus convex towards the image side. Thus, a moving stroke for the third lens unit L**3** is secured.

In an exemplary embodiment, the third lens unit L**3** moves towards the object side during zooming. Thus, the third lens unit L**3** and the fourth lens unit L**4** bear the magnification allocation.

Further, the first lens unit L**1**, having a positive refractive power, moves towards the object side so that the second lens unit L**2** can exert a high variable magnification effect.

Thus, the zoom lens according to an exemplary embodiment of the present invention can achieve a high zoom ratio without much increasing the refractive power of each of the first lens unit L**1** and the second lens unit L**2**.

Furthermore, an exemplary embodiment employs a rear focusing method. That is, in an exemplary embodiment, the fifth lens unit L**5**, which is light in weight, moves along the optical axis to perform focusing.

In an exemplary embodiment, the light-weighted fifth lens unit L**5** moves for focusing. Accordingly, an exemplary embodiment can easily perform quick focusing (for example, automatic focusing).

Moreover, a lens unit to be selected as a unit for performing focusing is not limited to the fifth lens unit L**5**. That is, an exemplary embodiment of the present invention can be implemented by moving the fourth lens unit L**4** along the optical axis.

In an exemplary embodiment, the third lens unit L**3** is movable so that the third lens unit L**3** has a component perpendicular to the optical axis. Accordingly, an image shake occurring when the entire optical system is vibrated can be corrected.

With the above-described configuration, an exemplary embodiment can perform image stabilization without using any additional optical member (a variable angle prism, for example) or an additional lens unit for image stabilization. Therefore, an exemplary embodiment can prevent the entire zoom lens from becoming large-sized. Note that in the first, second, and fourth exemplary embodiments, the aperture stop SP moves integrally with the third lens unit L**3** during zooming.

Accordingly, the number of lens units, which may be required according to whether they serve as a movable lens unit or a stationary lens unit, can be reduced.

On the other hand, in the third exemplary embodiment, the aperture stop SP moves independently from the third lens unit L**3** during zooming. Thus, the position of the entrance pupil in an area in which the angle of view is wide can be close to the object side. Accordingly, the front lens diameter (the effective diameter of the first lens unit L**1**) can be kept small.

Note that in the case where the aperture stop SP is stationary, it is not necessary to move a diaphragm unit. Accordingly, this configuration can be advantageous in terms of power saving because in this case, a driving torque for driving an actuator that drives the diaphragm unit during zooming can be set low.

A lens configuration of each lens unit is described below.

To begin with, the first lens unit L**1** is described. The effective lens diameter of the first lens unit L**1** can be relatively large. Accordingly, it is more useful to use as small a number of lens elements as possible in terms of reducing the size and weight of the entire lens unit.

In an exemplary embodiment, the first lens unit L**1** includes three lenses, namely, a cemented lens composed of a negative lens and a positive lens and another positive lens. With this configuration, the zoom lens according to an exemplary embodiment of the present invention can reduce or suppress spherical aberration and chromatic aberration occurring when the zoom ratio is increased.

The second lens unit L**2** is described next. In the first and second exemplary embodiments, the second lens unit L**2** includes three mutually independent lens units, namely, a meniscus-shaped negative lens whose lens surface on the object side has a convex shape, a negative lens both of whose lens surfaces have a concave shape, and a positive lens whose surface on the object side has a convex shape. With this configuration, the zoom lens according to an exemplary embodiment of the present invention can reduce variation of aberration occurring during zooming. In particular, distortion occurring at the wide-angle end and spherical aberration occurring at the telephoto end can be effectively corrected.

In the third exemplary embodiment, the second lens unit L**2** includes three negative lenses and one positive lens in order from the object side. With the above-described configuration, the zoom lens according to an exemplary embodiment of the present invention can effectively correct off-axis aberration and is useful to increase the angle of view at the wide-angle end.

In the fourth exemplary embodiment, the second lens unit L**2** includes two negative lenses and a cemented lens composed of a positive lens and a negative lens in order from the object side. With the above-described configuration, the zoom lens according to an exemplary embodiment of the present invention can effectively reduce variation of chromatic aberration during zooming.

The third lens unit L**3** is described next. In the first, second, and third exemplary embodiments of the present invention, the third lens unit L**3** includes two positive lenses and a negative lens whose surface facing the image side has a concave shape. With this configuration, a principal point distance between the second lens unit L**2** and the third lens unit L**3** can be reduced. Accordingly, the length of the lens portion from the third lens unit L**3** to the fifth lens unit L**5** can be reduced.

In addition, in the first, second, and third exemplary embodiments, the third lens unit L**3** includes one or more aspheric surfaces. With this configuration, the zoom lens can effectively correct variation of aberration caused by zooming.

Furthermore, in the third exemplary embodiment, a cemented lens composed of a negative lens and a positive lens is included in the third lens unit L**3**. With this configuration, the zoom lens can reduce variation of chromatic aberration caused by zooming. Moreover, the zoom lens can reduce aberration occurring due to decentering at the time of image stabilization by decentering the third lens unit L**3** from the optical axis.

In the fourth exemplary embodiment, unlike the other exemplary embodiments of the present invention, the third lens unit L**3** includes a positive lens and a cemented lens. The cemented lens is composed of a positive lens and a meniscus negative lens having a convex shape facing the image side. With this configuration, in the fourth exemplary embodiment, aberration of an on-axis light flux can be effectively corrected and F-number can be decreased.

The fourth lens unit L**4** is described next. In the first through fourth exemplary embodiments, the fourth lens unit L**4** includes one negative lens whose surface on the object side has a convex shape or a cemented lens composed of a positive lens and a negative lens. In the fourth exemplary embodiment, the fourth lens unit L**4** has an aspheric surface. Thus, variation of aberration occurring during zooming can be reduced by the aspheric surface.

The fifth lens unit L**5** is described next. In the case where the fifth lens unit L**5** includes one positive lens, the positive lens is made of a glass material having a low dispersion characteristic. With this configuration, variation of chromatic aberration occurring during focusing can be reduced. On the other hand, in the case where the fifth lens unit L**5** includes two or more lenses, the fifth lens unit L**5** can include a cemented lens to reduce variation of chromatic aberration occurring during focusing.

With the above-described configuration, an exemplary embodiment of the present invention can achieve a zoom lens having a high zoom ratio, whose front lens diameter is small, whose retracted lens length is short, and whose entire size is small.

In addition, with the above-described configuration, an exemplary embodiment of the present invention can achieve a zoom lens having a high zoom ratio, whose entire size is small.

It is further useful if an exemplary embodiment satisfies at least one of the following conditions. In this case, an effect corresponding to each condition can be obtained.

In the conditions, f**2** denotes a focal length of the second lens unit L**2**, fw denotes a focal length of the entire zoom lens at the wide-angle end, ft denotes a focal length of the entire zoom lens at the telephoto end, β**2** denotes a ratio (β**2**t/β**2**w) of an imaging magnification (β**2**t) of the second lens unit L**2** at the telephoto end to an imaging magnification (β**2**w) of the second lens unit L**2** at the wide-angle end, β**3** denotes a ratio (β**3**t/β**3**w) of an imaging magnification (β**3**t) of the third lens unit L**3** at the telephoto end to an imaging magnification (β**3**w) of the third lens unit L**3** at the wide-angle end, m**1** denotes an amount of movement of the first lens unit L**1** during zooming from the wide-angle end to the telephoto end, m**2** denotes an amount of movement of the second lens unit L**2** during zooming from the wide-angle end to the telephoto end, where the amount of movement is a difference between a position of the moving lens unit with respect to the image plane at the wide-angle end and a position of the moving lens unit with respect to the image plane at the telephoto end and its sign is positive when the position is displaced to the image side at the telephoto end with respect to the wide-angle end, fm ($fm=\sqrt{(fw\cdot ft)}$) denotes a focal length of the entire zoom lens at a middle zoom position, bfm denotes an air-equivalent optical path length from a surface of the fifth lens unit L**5** located closest to the image side (a surface having a refractive power) to the image plane at the middle zoom position, and bft denotes an air-equivalent optical path length from a surface of the fifth lens unit L**5** located closest to the image side (a surface having a refractive power) to the image plane at the telephoto end.

The following condition can be satisfied:

$$-0.7<f2/\sqrt{(fw\cdot ft)}<-0.2 \quad (1)$$

The condition (1) is concerned with achieving a high zoom ratio for the zoom lens by appropriately selecting the focal length of the second lens unit L**2**. If the focal length of the second lens unit L**2** becomes short exceeding the lower limit of the condition (1), a high zoom ratio can be achieved with a small movement stroke, but aberration occurring due to an increase in refractive power increases, which is difficult to correct.

If the focal length of the second lens unit L**2** becomes long exceeding the upper limit of the condition (1), it is necessary to increase the amount of movement of each lens unit to achieve a high zoom ratio. In this case, it is difficult to achieve a small-sized zoom lens.

It is further useful if the zoom lens according to an exemplary embodiment satisfies one or more of the following conditions:

$$1.5<\beta2/\beta3<9.0 \quad (2)$$

$$-7.0<m1/m2<-1.0 \quad (3)$$

$$1.2<bfm/bft<3.0 \quad (4)$$

Each exemplary embodiment can achieve an effect corresponding to each condition by satisfying the same.

A technical significance of each condition is described below.

The condition (2) is concerned with a variable magnification allocation of the second lens unit L**2** and the third lens unit L**3**. In the zoom type of each exemplary embodiment, the second lens unit L**2** mainly performs variable magnification. If a variable magnification allocation of the second lens unit L**2** becomes small exceeding the lower limit of the condition (2), it becomes difficult to achieve a high zoom ratio.

On the other hand, if a variable magnification allocation of the second lens unit L**2** becomes large exceeding the upper limit of the condition (2), the variable magnification effect by the second lens unit L**2** becomes too high. This is not useful because, in this case, variation of aberration occurring during zooming and sensitivity to decentering may increase.

The condition (3) is concerned with an appropriate ratio of the amount of movement of the first lens unit L**1** to that of the second lens unit L**2** during zooming. If the lower limit of the condition (3) is exceeded, the amount of movement of the second lens unit L**2** becomes too large compared to that of the first lens unit L**1**. In this case, the distance between the surface of the second lens unit L**2** located closest to the object side and the aperture stop SP becomes large at the wide-angle end. Accordingly, the position of the entrance pupil comes close to the image side.

As a result, the vertical position (height) of the incident off-axis ray becomes very high near the wide-angle end. Accordingly, the front lens diameter may increase. Thus, it becomes difficult to achieve a small-sized zoom lens.

If the upper limit of the condition (3) is exceeded, the amount of movement of the first lens unit L**1** becomes too large. Accordingly, the vertical position (height) of the incident off-axis ray becomes very high at the telephoto end. In this case, the front lens diameter increases, which is not useful.

The condition (4) is concerned with an appropriate interval between the fifth lens unit L**5** and the image plane.

It is useful that a sufficiently wide interval between the fourth lens unit L**4** and the fifth lens unit L**5** is secured near the telephoto end to secure a traveling amount of each lens unit so as to achieve a high zoom ratio.

If the interval between the fourth lens unit L**4** and the fifth lens unit L**5** is simply increased, the entire length of the zoom lens may increase. In this regard, it is useful that the fifth lens unit L**5** moves towards the object side in the middle zooming range and moves towards the image side near the telephoto end.

The upper limit value and the lower limit value of the condition (4) define a condition for appropriately downsizing (reducing the entire length of) the zoom lens while achieving a high zoom ratio. If the lower limit of the condition (4) is exceeded, it becomes difficult to secure a sufficient amount of movement of each lens unit during focusing on a close object. In this case, with respect to the variable magnification allocation of the fifth lens unit L**5**, the variable magnification effect of the fifth lens unit L**5** may be reduced. This is not useful in achieving a high zoom ratio.

On the other hand, if the upper limit of the condition (4) is exceeded, although it is useful in achieving a high zoom ratio, sensitivity to focusing may decrease. As a result, in this case, it becomes difficult to correct variation of focusing occurring due to part tolerance or temperature change with the fifth lens unit L**5**.

In an exemplary embodiment, in order to achieve a high zoom ratio while effectively correcting aberration and reducing variation of aberration occurring during zooming, it is further useful to set the range of the values in the conditions (1) through (4) as follows:

$$-0.7<f2/\sqrt{(fw\cdot ft)}<-0.25 \quad (1a)$$

$$2.0<\beta 2/\beta 3<7.0 \quad (2a)$$

$$-5.0<m1/m2<-1.8 \quad (3a)$$

$$1.3<bfm/bft<2.5 \quad (4a).$$

With the above-described configuration, an exemplary embodiment can achieve a small-sized zoom lens having a high zoom ratio, whose entire lens length is short, by appropriately setting the amount of movement of each lens unit during zooming and the refractive power of each lens unit.

In particular, an exemplary embodiment having the above-described configuration can achieve a zoom lens having a high optical performance over the entire zooming range from the wide-angle end to the telephoto end.

Hereinbelow, numerical examples (1) through (4) of zoom lenses corresponding to the first through fourth exemplary embodiments of the present invention are set forth. In each numerical example, "i" denotes the order of an optical surface from the object side, "ri" denotes a radius of curvature of the i-th lens surface, "di" denotes a lens thickness or an air space between the i-th surface and the (i+1)-th surface, "ni" and "vi" respectively denote a refractive index and an Abbe number of the material of the i-th optical member with respect to d-line light.

The aspheric shape is expressed as follows:

$$x=(h^2/R)/[1+[1-(1+k)(h/R)^2]^{1/2}+Bh^4+Ch^6+Dh^8+Eh^{10}$$

where "k" denotes eccentricity (conical coefficient), "B", "C", "D", and "E" denote aspheric coefficients, "x" denotes a displacement from a surface vertex along the optical axis in a position at a height "h" from the optical axis, and "R" denotes a paraxial radius of curvature.

Furthermore, "E−Z" denotes "10^{-Z}". In addition, two surfaces closest to the image side represent an optical block, such as a filter or a face plate.

In addition, the relationship between each condition and each numerical example is set forth in Table 1. "BF" denotes a distance from a surface closest to the image plane to the image plane.

Numerical Example 1
Unit: mm

r1 = 70.9695	d1 = 1.300	nd1 = 1.806100	vd1 = 33.3
r2 = 32.9073	d2 = 4.500	nd2 = 1.496999	vd2 = 81.5
r3 = −111.7649	d3 = 0.100		
r4 = 26.7420	d4 = 2.400	nd3 = 1.603112	vd3 = 60.6
r5 = 52.6149	d5 = Variable		
r6 = 28.2339	d6 = 0.700	nd4 = 1.882997	vd4 = 40.8
r7 = 6.1390	d7 = 2.600		
r8 = −22.7407	d8 = 0.600	nd5 = 1.696797	vd5 = 55.5
r9 = 23.8455	d9 = 0.400		
r10 = 12.0313	d10 = 1.700	nd6 = 1.922860	vd6 = 18.9
r11 = 37.6285	d11 = Variable		
r12 = Stop	d12 = 1.500		
r13 = 13.8130	d13 = 2.000	nd7 = 1.693500	vd7 = 53.2
r14* = −95.8833	d14 = 3.000		
r15 = 51.5950	d15 = 0.600	nd8 = 1.846660	vd8 = 23.9
r16 = 10.7382	d16 = 0.272		
r17 = 11.7596	d17 = 1.700	nd9 = 1.603112	vd9 = 60.6
r18 = −18.7628	d18 = Variable		
r19 = 29.5071	d19 = 1.200	nd10 = 1.761821	vd10 = 26.5
r20 = 51.5358	d20 = 0.600	nd11 = 1.603112	vd11 = 60.6
r21 = 10.0344	d21 = Variable		
r22 = 18.6244	d22 = 3.200	nd12 = 1.804000	vd12 = 46.6
r23 = −12.1545	d23 = 0.600	nd13 = 1.805181	vd13 = 25.4
r24 = −54.2790	d24 = Variable		
r25 = ∞	d25 = 1.200	nd14 = 1.516330	vd14 = 64.1
r26 = ∞	d26 = BF		

Aspheric Coefficients

r14	k = −1.41507E+03	B = −5.53469E−05	C = 7.53066E−06
	D = −1.49270E−07		

Various Data
Zoom Ratio: 14.75

	Wide-Angle End	Middle Position	Telephoto End
Focal Length	6.10	23.40	89.99
F-number	2.90	3.26	4.29
Angle of View	30.3	8.7	2.3
Image Height	3.6	3.6	3.6
Lens Total Length	67.99	82.94	98.99
BF	8.27	14.63	6.14
d5	0.70	23.50	38.58
d11	19.78	3.83	1.53
d18	1.50	3.55	3.65
d21	8.76	8.45	20.13
d24	5.58	11.94	3.44

Lens Unit Data

Lens Unit	Starting Surface	Focal Length
1	r1	56.05
2	r6	−8.53
3	r12	14.05
4	r19	−27.98
5	r22	17.68

Numerical Example 2
Unit: mm

r1 = 37.4429	d1 = 1.100	nd1 = 1.805181	vd1 = 25.4
r2 = 24.2372	d2 = 3.300	nd2 = 1.487490	vd2 = 70.2
r3 = 110.4237	d3 = 0.200		

-continued

Numerical Example 2
Unit: mm

r4 = 32.7375	d4 = 2.500	nd3 = 1.696797	νd3 = 55.5
r5 = 153.2020	d5 = Variable		
r6 = 26.3687	d6 = 0.800	nd4 = 1.804000	νd4 = 46.6
r7 = 6.5704	d7 = 3.89340		
r8 = −18.9046	d8 = 0.700	nd5 = 1.603112	νd5 = 60.6
r9 = 26.4998	d9 = 0.700		
r10 = 13.7742	d10 = 1.600	nd6 = 1.922860	νd6 = 18.9
r11 = 30.6924	d11 = Variable		
r12 = Stop	d12 = 2.200		
r13* = 9.2003	d13 = 3.000	nd7 = 1.583126	νd7 = 59.4
r14 = −61.1241	d14 = 2.400		
r15 = 25.9673	d15 = 0.700	nd8 = 1.846660	νd8 = 23.9
r16 = 8.7391	d16 = 0.800		
r17 = 25.1623	d17 = 2.000	nd9 = 1.487490	νd9 = 70.2
r18 = −21.3178	d18 = Variable		
r19 = 38.4933	d19 = 1.000	nd10 = 1.487490	νd10 = 70.2
r20 = 22.0000	d20 = Variable		
r21 = 13.4000	d21 = 2.000	nd11 = 1.487490	νd11 = 70.2
r22 = −175.1720	d22 = Variable		
r23 = ∞	d23 = 0.800	nd12 = 1.498310	νd12 = 65.1
r24 = ∞	d24 = BF		

Aspheric Coefficients

r13	k = −2.49846	B = 2.27368E−4	C = −6.59585E−7
	D = −9.99386E−8		
	E = 3.92484E−9		

Various Data
Zoom Ratio: 13.33

	Wide-Angle End	Middle Position	Telephoto End
Focal Length	6.00	21.90	79.99
F-number	3.34	3.84	4.95
Angle of View	30.9	9.3	2.6
Image Height	3.6	3.6	3.6
Lens Total Length	69.63	77.05	89.11
BF	10.62	15.65	7.45
d5	0.80	18.73	30.24
d11	24.53	7.94	1.69
d18	2.16	2.31	5.57
d20	2.63	3.73	15.27
d22	5.10	10.13	1.92

Lens Unit Data

Lens Unit	Starting Surface	Focal Length
1	r1	48.43
2	r6	−9.05
3	r12	17.91
4	r19	−107.46
5	r21	25.62

Numerical Example 3
Unit: mm

r1 = 75.6161	d1 = 1.900	nd1 = 1.806100	νd1 = 33.3
r2 = 38.4904	d2 = 5.500	nd2 = 1.496999	νd2 = 81.5
r3 = 1574.3184	d3 = 0.200		
r4 = 40.1987	d4 = 4.300	nd3 = 1.603112	νd3 = 60.6
r5 = 195.3611	d5 = Variable		
r6 = 43.9723	d6 = 1.000	nd4 = 1.882997	νd4 = 40.8
r7 = 10.3266	d7 = 2.700		
r8 = 25.5214	d8 = 0.850	nd5 = 1.834807	νd5 = 42.7
r9 = 10.7219	d9 = 3.600		
r10 = −23.5964	d10 = 0.800	nd6 = 1.834807	νd6 = 42.7
r11 = −171.2663	d11 = 0.116		

-continued

Numerical Example 3
Unit: mm

r12 = 21.7930	d12 = 2.250	nd7 = 1.922860	νd7 = 18.9
r13 = 487.0594	d13 = Variable		
r14 = Stop	d14 = Variable		
r15* = 12.0562	d15 = 3.450	nd8 = 1.583126	νd8 = 59.4
r16 = −82.0366	d16 = 2.800		
r17 = 42.0042	d17 = 1.150	nd9 = 1.603420	νd9 = 38.0
r18 = 12.5862	d18 = 0.300		
r19 = 21.2243	d19 = 0.800	nd10 = 2.003300	νd10 = 28.3
r20 = 8.5720	d20 = 2.150	nd11 = 1.719995	νd11 = 50.2
r21 = −58.7695	d21 = Variable		
r22 = 55.2648	d22 = 1.000	nd12 = 1.761821	νd12 = 26.5
r23 = 69.9209	d23 = 0.600	nd13 = 1.603112	νd13 = 60.6
r24 = 18.0000	d24 = Variable		
r25 = 20.2436	d25 = 4.000	nd14 = 1.772499	νd14 = 49.6
r26 = −9.8847	d26 = 0.600	nd15 = 1.806100	νd15 = 33.3
r27 = −50.8951	d27 = Variable		
r28 = ∞	d28 = 0.800	nd16 = 1.516330	νd16 = 64.1
r29 = ∞	d29 = BF		

Aspheric Coefficients

r15	k = 2.38663E−01	B = −9.34063E−05	C = −4.27892E−07
	D = 3.73118E−08	E = −1.75451E−09	

Various Data
Zoom Ratio: 17.48

	Wide-Angle End	Middle Position	Telephoto End
Focal Length	5.15	21.52	89.99
F-number	2.87	3.85	5.22
Angle of View	36.8	10.1	2.4
Image Height	3.9	3.9	3.9
Lens Total Length	92.73	102.23	125.15
BF	10.53	17.93	10.75
d5	0.90	25.33	46.76
d13	25.63	5.06	1.76
d14	10.21	3.52	1.78
d21	1.00	4.56	13.30
d24	4.40	5.77	10.74
d27	8.00	15.39	8.22

Lens Unit Data

Lens Unit	Starting Surface	Focal Length
1	r1	70.34
2	r6	−10.20
3	r15	19.96
4	r22	−46.37
5	r25	20.27

Numerical Example 4
Unit: mm

r1 = 129.3681	d1 = 3.000	nd1 = 1.846660	νd1 = 23.9
r2 = 76.8780	d2 = 7.500	nd2 = 1.583126	νd2 = 59.4
r3 = 3331.9206	d3 = 0.200		
r4 = 74.1874	d4 = 4.500	nd3 = 1.696797	νd3 = 55.5
r5 = 138.3490	d5 = Variable		
r6 = 52.4076	d6 = 1.500	nd4 = 1.834807	νd4 = 42.7
r7 = 13.9045	d7 = 7.800		
r8 = −96.1039	d8 = 1.100	nd5 = 1.772499	νd5 = 49.6
r9 = 43.8328	d9 = 0.700		
r10 = 23.0329	d10 = 4.400	nd6 = 1.846660	νd6 = 23.9
r11 = −166.9463	d11 = 1.100	nd7 = 1.834807	νd7 = 42.7
r12 = 40.9356	d12 = Variable		
r13 = Stop	d13 = 2.850		

-continued

Numerical Example 4 Unit: mm			
r14 = 55.4646	d14 = 2.600	nd8 = 1.696797	νd8 = 55.5
r15 = −37.4229	d15 = 0.500		
r16 = 143.4269	d16 = 3.400	nd9 = 1.603112	νd9 = 60.6
r17 = −18.5766	d17 = 0.800	nd10 = 1.846660	νd10 = 23.9
r18 = −52.0513	d18 = Variable.		
r19* = −16.4692	d19 = 2.500	nd11 = 1.688931	νd11 = 31.1
r20 = −12.3790	d20 = 1.000	nd12 = 1.516330	νd12 = 64.1
r21 = 202.3067	d21 = Variable		
r22 = 19.1851	d22 = 5.000	nd13 = 1.696797	νd13 = 55.5
r23 = −43.2878	d23 = 0.200		
r24 = 15.6598	d24 = 5.000	nd14 = 1.496999	νd14 = 81.5
r25 = −19.3663	d25 = 0.800	nd15 = 1.806100	νd15 = 33.3
r26 = 18.4800	d26 = 1.300		
r27 = −180.4304	d27 = 2.400	nd16 = 1.583126	νd16 = 59.4
r28* = −51.6191	d28 = Variable		
r29 = ∞	d29 = 3.500	nd17 = 1.516330	νd17 = 64.2
r30 = ∞	d30 = BF		

Aspheric Coefficients			
r19	k = 1.48433E−1	B = 1.54153E−5	C = 3.68917E−7
	D = −7.67521E−9		
r28	k = −7.84496E+1	B = 5.99482E−5	C = 5.10736E−7
	D = −1.13419E−9		

Various Data
Zoom Ratio: 12.11

	Wide-Angle End	Middle Position	Telephoto End
Focal Length	7.44	25.87	90.17
F-number	2.50	3.10	3.60
Angle of View	36.5	12.0	3.5
Image Height	5.5	5.5	5.5
Lens Total Length	128.58	148.52	192.40
BF	11.59	14.85	10.57
d5	1.00	39.98	85.65
d12	40.33	9.34	1.80
d18	1.29	14.03	22.87
d21	14.22	10.17	11.35
d28	3.70	6.96	2.68

Lens Unit Data

Lens Unit	Starting Surface	Focal Length
1	r1	135.38
2	r6	−17.77
3	r13	26.64
4	r19	−33.58
5	r22	21.41

TABLE 1

	Numerical Example 1	2	3	4
Condition (1)	−0.36	−0.41	−0.47	−0.69
Condition (2)	6.26	4.98	3.08	2.23
Condition (3)	−4.51	−1.95	−2.41	−3.06
Condition (4)	2.38	2.10	1.67	1.40

An exemplary embodiment of a digital still camera (image pickup apparatus) that uses a zoom lens according to an exemplary embodiment of the present invention as a photographic optical system is described below with reference to FIG. **13**.

Referring to FIG. **13**, the digital still camera includes a camera body **20**, a photographic optical system **21** that

includes a zoom lens according to an exemplary embodiment of the present invention, and a solid-state image sensor (photoelectrical conversion element) **22**, such as a CCD sensor or a CMOS sensor, that receives an object image formed by the photographic optical system **21**. The digital still camera further includes a memory **23** configured to record information corresponding to an object image photoelectrically converted by the solid-state image sensor **22**. The digital still camera further includes a viewfinder **24** that includes a liquid crystal display panel configured to allow a user to observe an object image formed on the solid-state image sensor **22**.

As described above, the zoom lens according to an exemplary embodiment of the present invention can be applied to an image pickup apparatus, such as a digital still camera, to implement a small-sized image pickup apparatus having a high optical performance.

While the present invention has been described with reference to exemplary embodiments, it is to be understood that the invention is not limited to the disclosed exemplary embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all modifications, equivalent structures, and functions.

This application claims priority from Japanese Patent Application No. 2007-287273 filed Nov. 5, 2007, which is hereby incorporated by reference herein in its entirety.

What is claimed is:

1. A zoom lens comprising, in order from an object side to an image side:

a first lens unit having a positive refractive power and configured to move along an optical axis during zooming;

a second lens unit having a negative refractive power and configured to move with a locus convex towards the image side during zooming;

a third lens unit having a positive refractive power; and

a fourth lens unit having a negative refractive power,

wherein the first lens unit is located closer to the object side at a telephoto end than at a wide-angle end,

wherein the second lens unit is located closer to the image side at the telephoto end than at the wide-angle end, and

wherein a focal length of the second lens unit (f**2**), a focal length of the zoom lens at the wide-angle end (fw), and a focal length of the zoom lens at the telephoto end (ft) satisfy the following condition:

$$-0.7<f2/\sqrt{(fw \cdot ft)}<-0.2.$$

2. The zoom lens according to claim **1**, wherein a ratio of an imaging magnification of the second lens unit at the telephoto end to an imaging magnification of the second lens unit at the wide-angle end (β**2**) and a ratio of an imaging magnification of the third lens unit at the telephoto end to an imaging magnification of the third lens unit at the wide-angle end (β**3**) satisfy the following condition:

$$1.5<\beta 2/\beta 3<9.0.$$

3. The zoom lens according to claim **1**, wherein an amount of movement of the first lens unit during zooming from the wide-angle end to the telephoto end (m**1**) and an amount of movement of the second lens unit during zooming from the wide-angle end to the telephoto end (m**2**) satisfy the following condition:

$$-7.0<m1/m2<-1.0.$$

4. The zoom lens according to claim **1**, further comprising a fifth lens unit having a positive refractive power and located closer to the image side than the fourth lens unit.

5. The zoom lens according to claim **4**, wherein the fifth lens unit is configured to move with a locus convex towards the object side during zooming.

6. The zoom lens according to claim **4**, wherein, when a focal length of the zoom lens at a middle zoom position (fm) is defined as $fm=\sqrt{(fw \cdot ft)}$, an air-equivalent optical path length from a surface of the fifth lens unit located closest to the image side to an image plane at the middle zoom position (bfm) and an air-equivalent optical path length from a surface of the fifth lens unit located closest to the image side to the image plane at the telephoto end (bft) satisfy the following condition:

$$1.2<bfm/bft<3.0.$$

7. The zoom lens according to claim **1**, wherein the first through fourth lens units are configured to move during zooming.

8. The zoom lens according to claim **1**, wherein the first lens unit is configured to move with a locus convex towards the image side during zooming.

9. The zoom lens according to claim **1**, further comprising a stop located between the second lens unit and the third lens unit and configured to move independently from each of the first through fourth lens units during zooming.

10. The zoom lens according to claim **1**, wherein the zoom lens is configured to form an image on a solid-state image sensor.

11. An image pickup apparatus comprising:

the zoom lens according to claim **1**; and

a solid-state image sensor configured to receive an image formed by the zoom lens.

* * * * *